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A fireworks model for Gamma-Ray Bursts

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ABSTRACT

The energetics of the long duration GRB phenomenon is compared with models of a rotating Black Hole (BH) in a strong magnetic field generated by an accreting torus. A rough estimate of the energy extracted from a rotating BH with the Blandford-Znajek mechanism is obtained with a very simple assumption: an inelastic collision between the rotating BH and the torus. The GRB energy emission is attributed to an high magnetic field that breaks down the vacuum around the BH and gives origin to a $e^{\pm}$ fireball. Its subsequent evolution is hypothesised, in analogy with the in-flight decay of an elementary particle, to evolve in two distinct phases. The first one occurs close to the engine and is responsible of energising and collimating the shells. The second one consists of a radiation dominated expansion, which correspondingly accelerates the relativistic photon–particle fluid and ends at the transparency time. This mechanism simply predicts that the observed Lorentz factor is determined by the product of the Lorentz factor of the shell close to the engine and the Lorentz factor derived by the expansion. An anisotropy in the fireball propagation is thus naturally produced, whose degree depends on the bulk Lorentz factor at the end of the collimation phase.

Key words: gamma–rays: bursts – X–rays: general – black hole physics

1 INTRODUCTION

At cosmological distances the observed GRB fluxes imply energies of order of up to a solar rest-mass ($\sim 10^{54}$ erg), and as they vary on timescales of the order of milli seconds from causality arguments these must arise in regions whose size is of the order of kilometres. This implies that an $e^{\pm}, \gamma$ fireball must form, which would expand relativistically. The fireball is energised and possibly collimated, mechanically or magnetically, close to the engine (for reviews see e.g. Piran 1999; Meszaros 2002). Subsequently it adiabatically expands and accelerates, until the Thomson transparency is reached (the opacity being determined by either electron–positron pairs or electrons if the fireball is baryon loaded). The GRB phenomenology – in particular the fast variability and the detection of γ–ray emission from an apparently compact region opaque to electron–positron production via photon–photon interaction – gives compelling reasons for the bulk motion of the emitting plasma to be highly relativistic with Lorentz factors of the order $\Gamma \sim 10^2 - 10^3$.

The degree of isotropy/collimation of the ejected fireball is however still unclear. In fact, as the observer only detects γ–ray flux from an angle $\sim \Gamma^{-1}$, it is not possible to simply discriminate between an isotropic and a jet-like structure from the observed GRB event. Nevertheless this is in principle possible by adequate sampling and determination of the behaviour of the light curves during the afterglow phase: following the deceleration/sideway expansion of the fireball more and more of the emitting plasma can be seen and a break (and steepening) in the light curve would appear when the whole of the volume becomes observable.

Indeed, recently a few GRB afterglows were observed at many wavelengths and suggest an axisymmetric jet-like structure for the fireball, thus strongly reducing the estimate of the energetics with respect to the isotropic case (Frail et al. 2001), although clearly increasing the required GRB rate. The temporal decays of the emission at different frequencies, interpreted according to the fireball model, suggest jet beaming with opening angles $\theta \sim 3^{\circ}$ (Frail et al. 2001). An important inference from these observations is also that the GRB have a typical energy with little intrinsic spread (Frail et al. 2001), although alternative possibilities, such as anisotropy of a collimated fireball, can account for the same observed phenomenology (Zhang & Meszaros 2002; Rossi, Lazzati & Rees 2002). Found observational trends among timing and spectral properties of GRB as well as numerical results appear also to favour anisotropic distributions of energy/velocity in the fireball (Lloyd-Ronning & Ramirez-Ruiz 2002; Salmonson & Galama 2002; Zhang, Woosley & MacFayden 2002).

A further important discovery made by *Beppo*SAX, ASCA and Chandra telescopes, is the presence of iron lines in the X-ray spectra of GRBs (e.g. Amati et al. 2000; Piro et al. 2000; Antonelli et al. 2000). This provides a power-

ful tool to understand the nature and the environment of GRB primary sources (Vietri et al. 2001; Rees & Mészáros 2000): strong iron lines imply a rich environment which may be an argument in favour of massive-star progenitor models of GRB (Woosley 1993, Paczynski 1993; Paczynski 1998; Vietri & Stella 1998). These findings have been recently accompanied by the claim of the observation of a complex of soft X–ray lines by XMM-Newton in the spectrum of GRB 011211 (Reeves et al. 2002, see also Watson et al. 2002). They suggest in particular that the high temperature derived from the emitting gas could be interpreted as reheating of pre-ejected material by the GRB itself.

These observations are in favour of the interpretation of GRBs as a second step of the residual of the primary explosion (e.g. Vietri & Stella 1998): the primary explosion leaves over a compact object that could be a rotating black hole, at the centre of a rarefied atmosphere of ejecta. In such scenario it is plausible that the energy extraction from a rotating BH, through the Blandford-Znajek (BZ) mechanism (Blandford & Znajek 1977, Lee et al. 2000), where the external magnetic field can be supplied by a torus circulating around the BH at a distance of the order of the Schwarzchild radius R_s.

In this paper we focus on two aspects of the 'standard' scenario for the GRB event. The first, developed in Section 2, concerns the extraction of energy from a rotating compact object and its conversion into a photon-e$^\pm$ fireball. Subsequently, in Section 3, we suggest that the acceleration and collimation could occur in two phases, the first one consists in energising and collimating the shells, the second one of a radiation dominated expansion. This mechanism predicts that the observed Lorentz factor is determined by the product of the Lorentz factor of the shell close to the engine and the Lorentz factor derived by the expansion, thus naturally giving rise to an anisotropic fireball. Our conclusions are reported in Section 4.

2 GAMMA-RAY BURST PROGENITOR

2.1 Energetics

As mentioned, Blandford and Znajek have proposed an interaction between a rotating BH and an accretion disk to explain the energetics of Active Galactic Nuclei. The same mechanism could be a good candidate for GRB engines as already pointed out (e.g. Paczynski 1998; Lee et al 2000). In the BZ mechanism the magnetic field of the accretion disk acts as a break on the BH and the energy output is mainly due to the loss of rotational energy. The rotational energy for a maximally rotating BH of mass $M_{\rm bh}$, with the rotation parameter $\tilde{a} = Jc/M_{\rm bh}^2 G = 1$, is 0.29 $M_{\rm bh}c^2$. Even with the optimal efficiency the available extractable energy for the BZ mechanism is (Lee et al 2000):

$$E_{\rm BZ} = 0.3 \times 10^{54} \left(\frac{M_{\rm bh}}{M_\odot}\right) \text{erg}.$$

In the following considerations it will be assumed that a dissipative interaction is at work between the BH and the torus surrounding it, due to an internal torque. If the short interaction is treated as an inelastic shock it is possible to apply the angular momentum conservation law

$$I_{\rm bh}\Omega_{\rm bh} + I_{\rm t}\Omega_{\rm t} = I\Omega,$$

where the subscripts 'bh' and 't' refer to the black hole and torus, respectively, and the right hand side quantities are those of the final BH slowed down by this interaction. In this approximation, the loss of rotational and gravitational energy (considering the torus approximately at the last stable orbit) can be derived as

$$\Delta E_{\rm rot} \simeq \frac{1}{2} I_{\rm bh}\Omega_{\rm bh}^2 \left(1 - \frac{I_{\rm bh}}{I}\right) = 2M_{\rm bh}^3\Omega_{\rm bh}^2 \left(1 - \frac{M_{\rm bh}^3}{M^3}\right) \sim$$

$$\sim 2M_{\rm bh}^3\Omega_{\rm bh}^2 \left(3\frac{M_{\rm t}}{M_{\rm bh}}\right) \simeq \frac{3}{2}\frac{a^2}{R_{\rm bh}^2} M_{\rm t} \simeq$$

$$\simeq 3E_{\rm rot,bh}\frac{M_{\rm t}}{M_{\rm bh}} \sim \frac{3}{8} M_{\rm t}c^2$$

$$\Delta E_{\rm g} = \frac{GM_{\rm t}M_{\rm bh}}{R_s} - \frac{GM_{\rm t}M_{\rm bh}}{3R_{\rm s}} \simeq \frac{1}{3} M_{\rm t}c^2 \ .$$

The total available energy is therefore $\Delta E_{\rm rot} + \Delta E_{\rm g} \simeq 0.7 M_{\rm t}c^2$, ranging between $10^{53} - 10^{54}$ erg for $M_{\rm t} = 0.1 - 1 M_\odot$. In the following it will be assumed that the energy source of the GRB is the gravitational collapse of a torus of 0.1 $M_\odot$ onto a rotating BH of 10 $M_\odot$.

2.2 Vacuum breakdown

A model for the generation of the GRB fireball is the vacuum breakdown in the volume close to the polar cap of the BH (Heyl 2001). A similar process in the proximity of a charged black hole has been considered by Ruffini and collaborators (e.g. Ruffini 1998).

The accreted material, which releases its gravitational energy, gives origin to a variable magnetic field: the field required to explain the high luminosity of GRB generates an electric field that could break down the vacuum.

In a recent analysis of the field around the BH Heyl (2001) obtained a value of $B_c \sim 4.5 \times 10^{13}$ G for the vacuum breakdown in the ergosphere. The corresponding magnetic energy density is $U_{\rm B} \simeq 8 \times 10^{25}$ erg cm^{-3}. An estimate of the electric energy density can be obtained by considering the Wald charge (Wald 1974), $Q_{\rm w} \sim 2BaM_{\rm bh}$ (in geometrical units) $\sim 2 \times 10^{16}$ C, corresponding to an electric field (at R_s) $E \simeq 2 \times 10^{15}$ V cm^{-1} and energy density of order $U_{\rm e} \simeq 2 \times 10^{24}$ erg cm^{-3}.

While the very same existence of the Wald charge has been questioned (Shatskiy 2001), similar results are obtained by considering the voltage drop created by the BZ mechanism

$$\Delta V = 10^{22} \left(\frac{M_{\rm bh}}{M_\odot}\right) \left(\frac{B}{10^{15}\text{G}}\right) \text{V},$$

which in the proximity of the BH corresponds to an electric

field

$$E = \frac{\Delta V}{2\pi R} = 5 \times 10^{15} \left(\frac{B}{10^{15}\mathrm{G}}\right) \frac{\mathrm{V}}{\mathrm{cm}}.$$

Therefore, considering the BZ mechanism to be responsible for energising GRBs, a magnetic field indeed of order $B \sim 10^{15}$G can account for the electric field required to break the vacuum. Nevertheless, in the following we will assume the description of the field around the BH obtained by Heyl (Heyl 2001).

In the proximity of the BH is thus possible to generate e$^{\pm}$ pairs which could give origin to the GRB fireball, provided a sufficiently clean environment in order to avoid previous electric field discharge. This condition can be verified if the relevant matter resides in the BH and in the rotating torus and the residual density close to the rotational axis is less than 10^{9} cm^{-3} (Shatskiy & Kardashev 2002, Goldreich & Julian 1969). Considering a typical electromagnetic field configuration around a Kerr BH (e.g. Punsly 2001), it is possible that initially the E field generated by the rotation of the BH in the magnetic field of the torus (e.g. Shatskiy 2001) can actually contribute to clear the environment of electron-proton plasma.

Note that the recent observation of GRB011211 by XMM (Reeves et al. 2002) reported an absorption edge at 1 keV with optical depth $\tau \sim 1$. If this evidence will be confirmed by other observations and assuming a homogeneous environment density, we could put a lower limit on the particle column density (10^{23} cm^{-2}) from the source to the X-ray photosphere, in favour of a relative clean environment at least on the jet axis direction.

2.3 The formation of the fireball

A magnetic field of the order of B_c breaks the vacuum in a volume $V \sim R_s^3$ (cf Heyl 2001).

The number of e$^{\pm}$ pairs would be

$$N_{\mathrm{e}^{\pm}} = 2 \times (2\pi)^3 \frac{V}{\lambda_{\mathrm{e}}^3} \simeq 10^{51},$$

considering for each e$^{\pm}$ pair a volume of the order of $(\lambda_e/2\pi)^3$ where λ_e is the electron Compton wavelength, with a corresponding particle density of $4{\times}10^{31}$ e$^{\pm}$ cm^{-3}. This density is evaluated for a single e$^{\pm}$ pair. For a large population it looks more adequate to adopt a typical white dwarf density, of order $\sim 4 \times 10^{29}$ cm^{-3} (Fermi 1966).

The available magnetic energy density for a field of order of B_c implies that each outgoing particle gets an energy $\epsilon_0 \sim 10^{-4}\eta_{\mathrm{acc}}$ erg, where η_{acc} is the acceleration efficiency. Its relativistic Lorentz factor is then $\gamma_0 = \epsilon_0/m_{\mathrm{e}}c^2 \sim 10^2\eta_{\mathrm{acc}}$.

After the formation of the plasmoid the particles undergo three important processes:

1) Particle acceleration in a time scale

$$t_{\mathrm{acc}} \sim \frac{10^2\eta_{\mathrm{acc}}m_{\mathrm{e}}c^2}{e \cdot E \cdot c} \sim 10^{-19}\eta_{\mathrm{acc}} \qquad \mathrm{s}$$

to acquire an energy $\sim 10^2\eta_{\mathrm{acc}}m_{\mathrm{e}}c^2$ in a electric field of the order of 2×10^{15} V/cm.

2) Single particle collimation in the direction of the magnetic field by synchrotron radiation. The particles momentum components normal to the magnetic field $p_{\perp}$ are damped in a time scale

$$t_{\mathrm{coll}} < \frac{\rho}{c \sin\lambda},$$

where the curvature radius ρ is of the order of $\sim 3 \times 10^6 E(\mathrm{GeV})/\mathrm{B(G)}$ cm and λ is the angle between the particle motion and the magnetic field. With the presence of a magnetic field of the order of 4×10^{13} G, the particles radiate all the energy corresponding to $p_{\perp}$ in a time scale

$$t_{\mathrm{coll}} \sim \frac{\eta_{\mathrm{acc}}}{\sin\lambda}10^{-19} \qquad \mathrm{s}.$$

The momentum components perpendicular to field line outside the plasmoid for all the particles are damped and the plasmoids becomes a stream of particles with velocity parallel to the external field lines with $\gamma \sim \gamma_0/3$. As a result the plasmoid travels as a parallel stream with bulk Lorentz factor

$$\Gamma_1 = \gamma \sim 30\,\eta_{\mathrm{acc}}.$$

3) Momenta randomisation on a time scale

$$t_{\mathrm{rand}} \sim l/c \sim 10^{-12}\eta_{\mathrm{acc}}^{-2} \qquad \mathrm{s},$$

where l is the mean free path for e$^{\pm}$ interaction, $l = (\sigma n)^{-1}$, using $\sigma = 87\mathrm{nb/E(GeV)}^2$ and $n = 8 \times 10^{29}$ cm^{-3}. The momenta randomisation will become more efficient considering the radiation field generated by the damping of the electrons in the magnetic field. To calculate the temperature of this electron-photon plasma we assume that all the initial magnetic energy remains confined in the same volume of the vacuum break-down. This density corresponds to a radiation gas with a temperature

$$T_0 = \left(\frac{B^2}{8\pi} \cdot \frac{1}{a}\right)^{1/4} \sim 10^{10}\mathrm{K}.$$

The corresponding mean free path in the comoving frame, using $\sigma_{\mathrm{compt}} \sim 1/3\sigma_{\mathrm{T}} \sim 2 \times 10^{-25}\mathrm{cm}^2$ and a radiation density $\sim 5 \times 10^{31}$ cm^{-3} is around $l \sim 10^{-7}$ cm. The observed time scale t_{rand} for this process is then

$$t_{\mathrm{rand}} \sim 10^{-16}\eta_{\mathrm{acc}} \qquad \mathrm{s}.$$

The energy of the particles in the plasmoid before the cooling by synchrotron emission is

$$E_{\mathrm{plasmoid}} = V\frac{B^2}{8\pi} \sim 10^{45}\mathrm{erg}.$$

The available energy in the overall inelastic collision is $\Delta E \sim 10^{53}$ erg, so that the emission of plasmoids could happen N_{plasmoid} times where:

$$N_{\mathrm{plasmoid}} \sim \eta_{\mathrm{B}}\frac{\Delta E}{E_{\mathrm{plasmoid}}} = 10^8\,\eta_{\mathrm{B}},$$

where we have taken into account also an efficiency, η_{B}, for conversion of mechanical energy into the electromagnetically generated e$^{\pm}$ fireball.

The model therefore predicts for long duration GRB a pulsed emission from $\sim 10^7\,\eta_{\mathrm{B},0.1}$ emitted plasmoids with an average time separation $\Delta t \sim t_{\mathrm{obs}}/N_{\mathrm{plasmoids}} \sim 10^{-5}$ s, corresponding to a separation distance $\sim 3 \times 10^5$ cm. This large number of shells are likely to merge, thus producing a significantly smaller number of well defined spikes in the

light curve with superposed a low amplitude flickering due to individual shells. The train of "sausage" plasmoids is 3×10^{12}cm long at the end of engine activity, even if its length could be slightly modified during the internal shock phase.

The overall time duration is dominated by the duration of the engine activity, the shortest variability time instead is determined by the plasmoids interactions. Variations in the observed luminosity can be due e.g. to the very same formation of (internal) shocks among the plasmoids and/or fluctuations in the accretion/field intensity.

3 COLLIMATION AND ACCELERATION: TWO PHASE EXPANSION

As already discussed under the fermion pressure the fireball would expand but the transversal motions are damped by the residual B which provides the $e^{\pm}$ plasma confinement and collimation and is responsible for synchrotron radiation. Thus the only motion possible for the plasma bunch is that parallel to B: the plasmoid thus becomes a stream of particles with velocity parallel to the external field lines (see Section 2.3) with a corresponding bulk Lorentz factor $\Gamma_1 \sim 30\,\eta_{\rm acc}$.

Within this scenario *, here we introduce the simplifying hypothesis that the jet evolution (as recalled above) is composed by two distinct phases, the first one (phase-1), occurring close to the engine responsible of energising and collimating the burst. Phase-1 ends (at R_1) when the pre–existent collimating mechanism (e.g. in the case of magnetic confinement the pre–existent magnetic field) cannot balance the jet pressure any further. We could give a rough estimation of R_1 considering the distance when the collimation time scale (for particles with $p_\perp \propto kT_0$) becomes equal to the randomisation time scale. Following the discussion of the previous Section, this happens when the external magnetic field is decayed to $B \sim 10^9$ G. Assuming a dependence to R^{-3} of the magnetic field, R_1 could be estimated at a distance $\sim 10^8$ cm.

It then follows the second phase (phase-2), which consists of adiabatic expansion and corresponding acceleration of the relativistic particle fluid. This phase lasts for the radiation dominated phase and ends at the smaller of the two radii (e.g. Piran 1999):

$$R_\eta = R_0 \frac{E}{Mc^2}$$

$$R_{\rm pair} = \left(\frac{3E}{4\pi R_0^3 a T_p^4} \right)^{1/4} R_0,$$

where R_0 is the initial source radius of the order of R_s, R_η is the radius where the fireball becomes matter dominated and $R_{\rm pair}$ where it becomes optically thin to pairs, corresponding to T_p around 20 keV. Assuming that the total mass of the shell is dominated by the electrons, which is justified by the very low environment density (estimated in Section 2.2 as $\sim 10^8$ cm^{-3}), these radii could be estimated as

$$R_\eta \sim 100 R_0 \qquad \text{and} \qquad R_{\rm pair} \sim 50 R_0.$$

Therefore, for a radiation dominated expansion (Paczynski 1986):

$$\frac{\Gamma_2^{'}}{\Gamma_1^{'}} \sim \frac{R_{\rm pair}}{R_0} \sim 50,$$

where $\Gamma_1^{'} \sim 2$ is derived by the mean energy after the collimation phase measured in the comoving frame of the collimated fireball shell, $\Gamma_2^{'}$ is the Lorentz factor at the end of phase 2 measured in the same reference frame.

At the moment of transparency the ejecta are moving according to the relativistic velocity composition in such a way that a particle accelerated during the radiation dominated expansion in the collimation direction will have

$$\Gamma_\parallel = 2\Gamma_1\Gamma_2^{'}$$

where $\Gamma_\parallel$ is the bulk Lorentz factor in the axis direction assuming Γ_1 as the Lorentz factor of the moving shell in the observer frame.

The opening angle of the conical jet structure generated at the end of the two phases is determined by the particles accelerated perpendicularly to the collimation moving with Lorentz factor $\Gamma_\perp = \Gamma_2^{'}$. The angle $\theta_{\rm c}$ with respect to the collimation axis is then:

$$\theta_{\rm c} \sim \tan\theta_{\rm c} = \frac{\Gamma_\perp}{\Gamma_1\Gamma_2^{'}} = \frac{\Gamma_2^{'}}{\Gamma_1\Gamma_2^{'}} = \frac{1}{\Gamma_1}.$$

Assuming $\Gamma_\parallel \sim 10^3$ (e.g. Lithwick & Sari 2001 for recent lower limit estimates) and estimating $\Gamma_2^{'} \sim 100$ from the previous considerations, the value Γ_1 at the end of the collimation phase has to be of the order of $\Gamma_1 \sim 5$ and consequently

$$\theta_{\rm c} \sim \frac{1}{\Gamma_1} \sim 2 \times 10^{-1}.$$

Values compatible with this estimate of Γ_1 have been derived in Section 2.3, with reasonable assumptions on $\eta_{acc} \sim 0.1$.

From the arguments presented here it follows that if the ejected shells are constituted by electron-positron pairs, travelling almost parallel at the end of phase-1, their internal energy, as provided by the central engine, corresponds to $\sim$ 1 MeV. The corresponding collimation is within an angle of order of a few degrees.

Furthermore, in the above scenario, the observed angular distribution of the expanding fireball is expected to be anisotropic and in particular is simply given by the following expression:

$$\tan(\theta) = \frac{\sin\theta^{'}}{\Gamma_1(\beta_1 + \cos\theta')},$$

where $\theta^{'}$ is the angle of the emitted particle in the frame of the expanding fireball.

The observed energy of the same particle could then be estimated as:

$$E(\theta') \propto \Gamma_1\Gamma_2^{'}(1 + \beta_2^{'}\cos\theta^{'}).$$

* We note that the collimation and acceleration process discussed in the following does qualitatively apply to a range of scenarios wider than that discussed in the previous section.

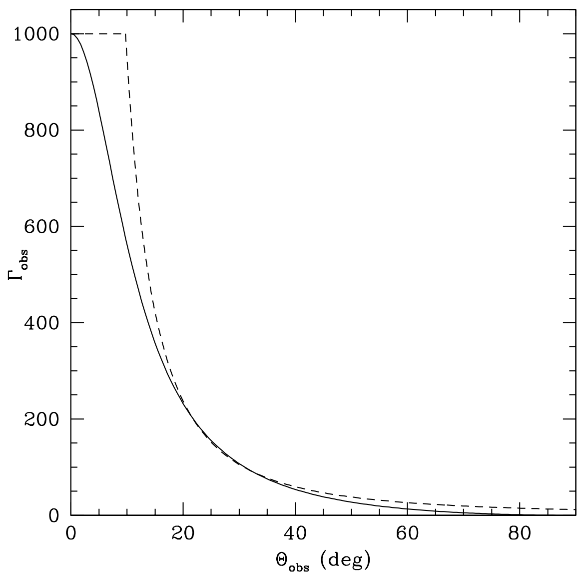

Figure 1. Predicted dependence of the energy as a function of the observing angle θ for $\Gamma_1 = 5$, $\Gamma_2' = 100$ and $\theta_c \sim \Gamma_1^{-1}$(solid line). For comparison we report as an example the indicative behaviour postulated by Rossi et al. (2002) for the corresponding value of $\theta_c = 10°$.

This angular distribution of the fireball Lorentz factor is shown in Fig. 1. Clearly, it is (qualitatively) expected a significant bias in the selection of bursts observed with a specific instrument (i.e. a defined energy window) not only because of flux but also peak energy limits. Note also that, intriguingly, the dependence of $E(\theta')$ is qualitatively similar to that postulated by Zhang & Meszaros (2002), Rossi et al. (2002) (reported as a reference example in Figure 1) to account for the phenomenological findings by Frail et al. (2001). It is also worth recalling the recent results by Lloyd–Ronning & Ramirez–Ruiz (2002) and Salmonson & Galama (2002) who find that observational (spectral and temporal) trends are better accounted for in models where the burst anisotropy can be ascribed to a dependence of the Lorentz factor (rather than barion loading) with angle from the jet axis, in agreement with the most direct predictions of the proposed scenario.

4 CONCLUSIONS

We considered the possibility that fireballs in long GRB are created by a high magnetic field that breaks down the vacuum around the BH and gives origin to a $e^{\pm}$ fireball. The energy can be extracted from a rotating BH via the Blandford-Znajek mechanism thanks to a strong magnetic field generated by an accreting torus.

The fireball evolution should then proceed in two phases, the first one consisting in the energisation and collimation of the shells by the external magnetic field and the second one - a radiation dominated expansion - corresponding to the acceleration of the relativistic photon–particle fluid and ending at the transparency radius. This scenario predicts that the resulting Lorentz factor is determined by the product of the Lorentz factor of the shell close to the engine and the Lorentz factor derived by the expansion and simply leads to the formation of an anisotropic fireball. For typical parameters expected in the model the opening angle of the jet obtained in this model could be then estimated to be of order of a few degrees, depending on the efficiency of the acceleration and the resulting angular dependence is similar to what already proposed in the literature on different grounds.

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